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Tomic, Tihomir ; Dominkovic, Dominik Franjo; Pfeifer, Antun; v, Daniel Rolph ; Pedersen, Allan Schrøder; Dui, Neven

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WASTE TO ENERGY PLANT OPERATION UNDER THE INFLUENCE OF MARKET AND LEGISLATION CONDITIONED CHANGES

Tihomir Tomić*

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

address: Ivana Lučića 5, 10 002 Zagreb, Croatia

e-mail: tihomir.tomic@fsb.hr

Dominik Franjo Dominković

Department of Energy Conversion and Storage, Technical University of Denmark (DTU)

Frederiksborgvej 399, 4 000 Roskilde, Denmark

e-mail: dodo@dtu.dk

Antun Pfeifer

SDEWES Centre

address: Ivana Lučića 5, 10 002 Zagreb, Croatia

e-mail: antun@sdewes.org

Daniel Rolph Schneider

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

address: Ivana Lučića 5, 10 002 Zagreb, Croatia

e-mail: daniel.schneider@fsb.hr

* Corresponding author

Allan Schrøder Pedersen
Department of Energy Conversion and Storage, Technical University of Denmark (DTU)
Frederiksborgvej 399, 4 000 Roskilde, Denmark
e-mail: alpe@dtu.dk

Neven Duić
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture
address: Ivana Lučića 5, 10 002 Zagreb, Croatia
e-mail: neven.duic@fsb.hr

ABSTRACT

In this paper, gate-fee changes of the waste-to-energy plants are investigated in the conditions set by European Union legislation and by the introduction of the new heat market. Waste management and sustainable energy supply are core issues of sustainable development of regions, especially urban areas. These two energy flows logically come together in the combined heat and power facility by waste incineration. However, the implementation of new legislation influences quantity and quality of municipal waste and operation of waste-to-energy systems. Once the legislation requirements are met, waste-to-energy plants need to be adapted to market operation. This influence is tracked by the gate-fee volatility. The operation of the waste-to-energy plant on electricity markets is simulated by using EnergyPLAN and heat market is simulated in Matlab, based on hourly marginal costs. The results have shown that the fuel switch reduced gate-fee and made the facility economically viable again. In the second case, the operation of the waste-to-energy plant on day-ahead electricity and heat market is analysed. It is shown that introducing heat market increased needed gate-fee on the

yearly level over the expected levels. Therefore, it can be concluded that the proposed approach can make projects of otherwise questionable feasibility more attractive.

KEYWORDS

Waste-to-energy, Combined heat and power, District heating, Power market, Dynamic heat market, Waste management legislation

1 INTRODUCTION

A large generation of waste per capita, out of which over a quarter is Municipal Solid Waste (MSW), classifies waste management (WM) as one of the core issues in sustainable development of EU regions. This problem is even more emphasized in urban and metropolitan areas with higher population density. With increasing population, energy consumption also increases. For that reason, urban energy systems have been analysed in many previous research papers. Urban solutions for district heating (DH), the data, and technologies, have been recently discussed in [1]. For such urban applications, optimal planning methods have been elaborated in [2], with the case of Russia. Relevant is also the study of the integration of high share of renewable energy sources [3], which stipulated that energy-only markets need to be addressed for the correct price signals and the flexible measures are of the key relevance for the high RES integration. In this context, flexible WtE CHP plant is a relevant factor in two energy markets: electricity and heat market. Therefore, integration of waste and energy systems represents the logical path in the sustainable development of regions. The importance of the usage of local energy sources in local energy systems, as well as their positive influence on the overall EU energy system, is emphasized in Heat Roadmap Europe [4],[5]. In this study, waste was classified as one of the primary heat sources in district heating systems (DHS). While waste and its energy recovery may seem as an ideal energy source for usage in urban areas, EU has identified the material potential of waste, which can be utilized through its material recovery. The first step in this direction was taken by Waste Framework Directive [6] which sets waste hierarchy by which primary step for recovery of produced waste is recycling (material recovery), while energy recovery is subordinated to it. A step further in the direction of material recovery was made by the Circular Economy Package [7] which defines more rigorous goals by increasing the share of MSW, which needs to be primarily separated and prepared for material recovery. These legislative changes have a great influence on waste quantities that are available for usage in waste-to-energy (WtE) based systems [8]. These changes in WMS can put feasibility of incineration-based WtE systems in question as burnable waste quantity decreases. This problem can be compensated by the introduction of new fuels such as biomass. Woody biomass, agricultural and forest residue [9], as well as biomass from short rotation coppice grown on unused agricultural land [10], showed great potential for use in energy systems and sustainability. Efficient use of locally available biomass was analysed in [11].

The use of biomass in WtE DH plant has proven to be a viable practice, as well as in co-combustion regime and as the use of mixed wastes (MW) for base load and biomass for peak load coverage [12], but time changes in waste quantity are not tracked. Use of WtE in conjunction with energy storage in variable electricity pricing environment, on industry scale, has been analysed and proven to justify a higher establishment cost of WtE [13].

During the lifetime of the WtE DH projects, a "business as usual" way of planning the waste incineration implies a constant increase of MSW quantity with a uniform quality. This is connected with increasing waste generation due to the growth of population and standard of living. This trend was already described by Kuznets curve hypothesis (EKC) which claims that economy growth (that can be defined by income per capita) has a negative impact on environment to a certain point after which environmental impact is reducing. This hypothesis was also adapted to MSW and called waste Kuznets curve hypothesis (WKC) and proved that household MSW generation per capita income also follows this correlation [14]. Also, this threshold was already reached by one part of the households/provinces in Japan [14] and Italy [15]. This trend shows that solving waste problem by building new waste disposal facilities can become unviable because increasing tendency in the MSW generation will come to an end. Furthermore, waste policies and instruments that encourage waste prevention can further decrease waste generation [15]. In the EU, the absolute decoupling trend is not present, but the elasticity of waste generation to income drivers is lower than in the past which indicates relative decoupling [16]. Also, current policies do not provide incentives for waste prevention, which will have to change. The introduction of new WM solutions, oriented to the reduction of waste production, re-using and recycling, reduces the amount of waste that needs to be disposed of [17]. The latter effect increases with time and can be viewed as a hazard for the feasibility of WM projects [8]. These effects are emphasized in new EU member states which have to quickly implement new WMS to achieve EU legislation goals but these systems also need to be economically sustainable. This should be done without drastically increasing the price of waste collection for the general population, as it would undermine waste collection system and cause problems such as illegal waste dumping. Therefore, the system needs to be designed to restrict volatility of gate-fees for waste treatment.

Reviewed literature did not sufficiently analyse time change of waste quantity and composition under the influence of WMS changes and its impact on WtE plants. Moreover, only in one paper [8] different ways of compensation of reduced waste quantities are analysed but the influence of secondary separation of waste was not considered. Furthermore, in [8] and [18] economic analysis of the operation of waste incinerators was considered, but their overall efficiency is rather low because of the emphasis on electricity generation. Also, in these papers the influence of gate-fee change was analysed only through arbitrary sensitivity analysis without consideration of the influence of other parameters on gate-fee value. Papers that analysed co-combustion of biomass with other fuels such as [19] did not deliberate big involuntary fuel substitution to sustain economic viability. The contribution of this work can be found in viability analysis of this possibility. In another part of this work, the focus was given to the market operation of considered facility. The influence which electricity grid tariffs have on flexible power to heat application was investigated in [20], but more research was done in the field of the possibility of plants operation on the open electricity market [21],[22]. As for the heat energy market, it is still in its infancy as most of the DHS are in public/municipality ownership. However, even in this segment, diversification of ownership is undergoing [23] which inevitably fosters the establishment of heat markets. Open DHS operation was already analysed [24] which consequently led to the analysis of waste incinerator operation on both energy markets in this paper. Upon the possible development of the dynamic heat market in Denmark, WtE plants could face the economic problems as they would not have guaranteed access to the DH market anymore. In addition, a local WtE plant can expect partial fuel switch in the foreseeable future due to a lack of economic feasibility of the waste import [25]. The contribution of this work can also be found in the economic analysis of dynamic WtE which operates on two markets. By introducing new fuel, WtE plant is already switching from operation in regulated conditions without third-party access which means a switch from stable fuel and energy prices to partially market defined fuel prices. On the other hand, after the transition to new WMS, WtE plants need to be ready to compete on open electricity and heat markets. By doing that, a care must be given to the gate-fee volatility, which is unavoidable in open market operations, while at the same time social-economic component of waste quantity and quality represents one more aggravating circumstance.

During the process of defining the case study, big difference in gate-fee values was observed across the EU - up to 176 €/t, calculated as a mean value with the addition of waste incineration tax [26]. Also, the difference in national legislations defines a wide range of tax values for different WM and disposal technologies. This is the result of the organization of the WM and its efficiency. Therefore, in this paper case studies of Croatia, where WMS does not meet EU criteria and has one of the lowest recycling rates, and Denmark, which has greatly exceeded the EU goals and is considered to be one of the most advanced systems that even makes extra income from the import and disposal of waste from neighbouring countries. This comparison extends the current knowledge by comparing the two extremes and leads to the conclusion that the investment in thermal waste treatment can be cost-effective in a wide range of configurations of WM system, without constituting an additional financial burden for the municipality or its citizens.

2 METHODS

The influence of adaptation to new WM legislation on WtE plants is tracked by analysing gate-fee volatility. Also, a method for adapting to expected changes in fuel supply of only planned WtE plant in Croatia and its management is proposed. To compensate for reducing the amount of primary fuel (waste), the share of secondary fuel is gradually increased until the final fuel shift is achieved. Fuel substitution is guided by waste amount prognosis in the analysed time period. This trend is pronounced in all new EU countries, which in the next couple of years have to invest a great effort to implement primary separation into WMS. Changes in the waste collection are expected in order to achieve EU goals gradually, but they cannot solve the waste disposal problem completely, so other ways to tackle this problem are explored. Implementation of other technologies, such as Mechanical Biological Treatment (MBT), is expected to further reduce the quantity of waste available for energy production.

To analyse these changes, production of MSW in the future years is needed to be forecasted. Future waste generation data were adapted from WM, literature or, where these data were not available, by usage of the LCA-IWM prognostic model [27]. In the novel model, the forecast of MSW waste generation and composition on the basis of actual data and a wide range of socio-economic data was taken into account. Also, legislation goals which define forecast boundaries were considered. Output data were structured as overall waste per fractions with and without MW fraction separately reported so all streams can be calculated as well as MW composition. The possibility of waste decoupling was not taken into account, as it was not expected and modelled in long-term projections. Changes expected due to intervention in the WMS were also tracked. LHV of waste were calculated by using the chemical composition of each waste fraction [28] through Mendeliev equation - Equation 1:

$$LHV = 4.187\big(81C + 300H - 26(O - S) - 6(9H + W)\big)\ [\frac{kJ}{kg}] \tag{1}$$

where C, H, O and S represents the share of corresponding chemical elements and W represents water share. The calculation of average LHV of mixed municipal waste is based on the calculated LHV of each fraction and physical composition of MW.

When existing WMS did not satisfy set goals, new WM scenarios were developed. The second scenario introduced MBT plant and is based on primary separation of waste, incineration, and MBT. All produced MSW, with the corresponding LHV, enters the incinerator only in the case of meeting legislation goals by source separation alone. Comparison of both scenarios for the case of legislation adaptation is shown in Figure 1.

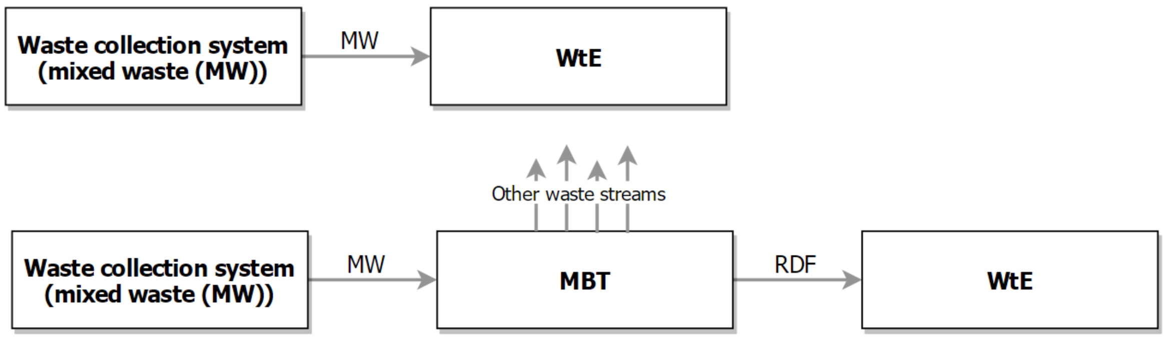

Figure 1. Comparison of the scenarios Without MBT and With MBT

Process flow data for MBT plant, which is introduced in scenario With MBT were adapted from the literature data [29]. As shown in Figure 2, MBT plant separates mainly bio-waste, metals, and glass, from the MW stream, which are prepared for material recovery processes. Another separated waste stream is Refuse-Derived Fuel (RDF) which is mainly composed of burnable fractions – paper and plastics, while the rest is unusable waste which is landfilled.

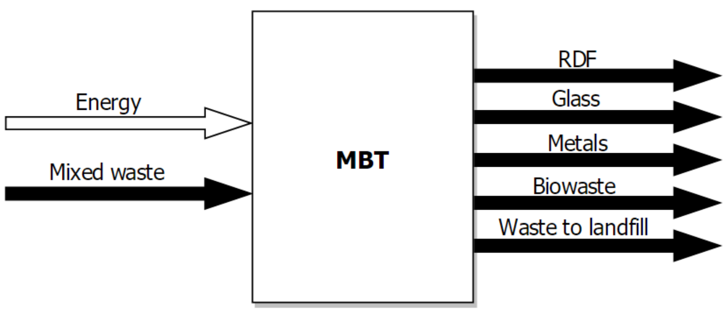

Figure 2. MBT process flows data

Waste components which are separated for material recovery do not contribute to the heating value of mixed MSW, so RDF stream's LHV is expected to increase. Quantity wise, this scenario further reduced available waste quantities for incineration and left space for introduction of second fuel.

To analyse the effect of legislation influenced waste reduction, as well as possible benefits from proposed compensation with secondary fuel, a gate-fee volatility analysis was conducted. The economic analysis was based on the case dependent conditions – national legislation as well as rules and regulations for system operation. The analysis tracked the minimum needed gate-fee to equalize annual cash flow to zero. This way of operation of municipal utility plants is logical because it is built with public funds to provide public service, not to make a profit. The operation of municipal facilities without generating a profit is regulated in some countries by local or national legislation. Example for this is Denmark, where this is regulated at the national level.

For analysing volatility of gate-fee due to the operation on energy markets, the case of Denmark facility is chosen because nationwide adaptation to EU waste legislation has already been done. This analysis was performed to investigate the influence of operating the WtE plant on both, electricity and heat markets. To interpret results, two scenarios were constructed, the first one that analysed WtE plant operation on electricity market alone and a second one that analysed its operation on both markets.

In the first scenario analysis of WtE plant operation on only one energy market, i.e. the el-spot day ahead market, was carried out. In this case, the heat was assumed to be sold within the municipality under the regulated conditions, without the third-party access.

For the second scenario analysis, the operation of the plant on two markets was assumed, an electricity market and a district heat day-ahead market. This case study was carried out in order to assess the prospects of the operation of the WtE plant on the dynamic heat day-ahead market that would operate on a similar principle as the electricity day-ahead market. As the heat day-ahead market is non-existent in Sønderborg, its hourly demand-supply curve was simulated in Matlab, based on the heating production plants' hourly marginal costs. A similar approach was adopted for the simulation of the heat day-ahead market for the Espoo city in Finland [19].

Marginal price of plants was calculated using the Equation 2:

$$MP = var_{O\&M} + fuel/\eta + tax_{fuel} - electricity_{income} - feed\_in_{premium} \tag{2}$$

MP denotes marginal price of heat generation in each hour for each heat generation plant and has the unit [€/MWh_{heat}]. Variable operating and maintenance cost is denoted as $var_{O\&M}$, fuel cost and efficiency as $fuel$ and η, while tax_{fuel} denotes tax imposed on the use of fuels for energy generation purposes. CHP plants generate income from electricity sales on power el-spot day ahead market and this income is represented by the $electricity_{income}$ term while waste CHP plant is also eligible for feed-in premium which is represented by the $feed\_in_{premium}$ term. The day ahead heat market was simulated using the case specific marginal heat generation costs of plants.

3 CASE STUDY

In order to investigate previously discussed changes in WMS and problems associated with them, the case study was created in which two cases were analysed: a potential project of incineration plant in Zagreb, Croatia, as the facility which is faced with upcoming challenges caused by harmonisation with EU waste legislation; and a case of the existing WtE plant in Sønderborg, Denmark, which is already operating on electricity market and faces the prospect of operating on both heat and electricity day ahead markets in the future.

3.1 Case of the Sønderborg municipality

The case of Sønderborg was used for market coupling analysis. Two scenarios were analysed – one based on the operation on electricity market (One energy market) and the second one, based on the operation on both electricity and heat markets (Two energy markets). DHS of the municipality of Sønderborg are well described in [30].

In Sønderborg municipality, approximately 160,000 tonnes of waste is collected every year out of which 45% is a household waste [31]. Waste is collected as separated waste streams and used for the production of electric and heat energy in incineration plant or used for material production, landfilled or processed in special treatment plants. In 2012, 74% of generated waste is collected for recycling. By municipal plans, these waste quantities are expected to grow as it is shown in Figure 3.

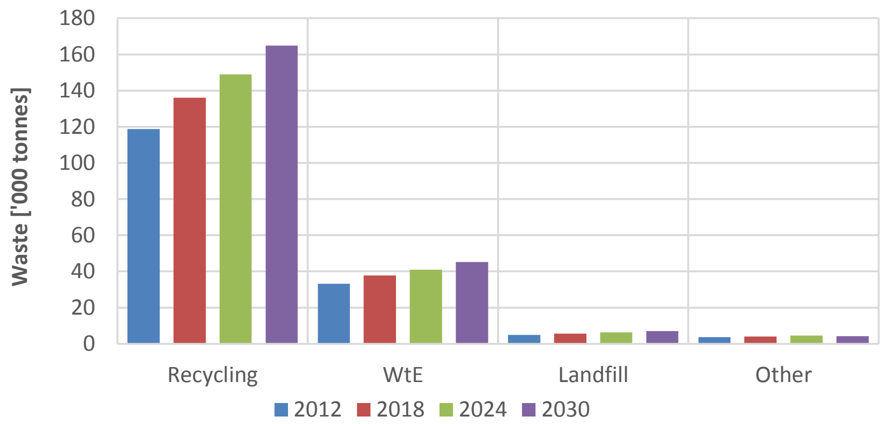

Figure 3. Waste quantities per disposal technologies - Sønderborg

Data for the years 2012, 2018 and 2024 were taken from existing plans [31], while 2030 data were obtained by linear extrapolation, as previous data showed linear time dependence. It was observed that waste quantities for all treatments are expected to increase.

Waste incineration CHP plant is a part of DH network in Sønderborg [32]. The plant is designed as combined cycle cogeneration plant with the conversion of waste energy in the steam cycle. Gas turbine waste heat is utilized for water pre-heating. It was designed to use 70% of natural gas and 30% of waste's energy but that ratio dropped to 0.3% for gas and 99.7% for waste in 2013. Also, the plant has achieved a gross efficiency of 90.5% in these new conditions and produced 160,148 MWh of heat and 36,069 MWh of electricity from waste with average LHV of 11.2 MJ/kg. The amount of treated waste is 69,630 tonnes from which 33,258 tonnes is from Sønderborg municipality while the rest was imported from Aabenraa municipality and supplemented with waste imported from England and Germany up to the maximum capacity of the plant.

Because of the lack of its own waste to fully utilize WtE plants, Denmark has been steadily increasing its waste import from the UK. Sønderborg WtE plant also utilizes imported waste as one part of the full supply. In general, the Danish plant can expect a gate-fee between 27 to 40 €/t of waste (depending on the season and the quality of the waste), after the costs of transportation and different fees are taken into account [33]. The gate-fee for the waste collected in Denmark is 27 €/t and it is the lowest gate-fee in Europe [34],[35]. Current incineration tax is approximately 44 €/t and this rate was used for both case studies. On top of the gate-fee that the WtE plants receive, there is a feed-in premium of 0.01 €/kWh of electricity sold to the market [34].

In the first scenario, One energy market scenario, the case of Sønderborg WtE plant operating only on one energy market is analysed. The plant is operating on the el-spot day ahead market, while the heat was assumed to be sold within the municipality under the regulated conditions, without the third-party access. This case study represents the current operating scheme of the plant in Sønderborg, as well as the case for most of the DH operators in Denmark. WtE plants are owned by municipalities in Denmark, and they are not allowed to operate with profits; they can only recover their operating costs and investments [35]. Furthermore, the project time needs to be matched with the anticipated lifetime of the energy plant. For the latter reason, a project lifetime of 20 years has been assumed, based on the technical data available [36]. According to Energinet.dk's recommendation (Danish power and gas TSO), a real discount rate of 4% was adopted [37].

For the second scenario, Two energy markets scenario, a day-ahead heat market had to be established as no such market exists in the municipality of Sønderborg currently. It was simulated using the marginal heat generation costs of plants obtained from the figures presented in Table 1.

Table 1. Costs used for establishing marginal heat price offers [36]

	Heat capacity [MW]	**Electric capacity [MW]**	η_e	η_{total}	**Variable cost [€/MWh$_{heat}$]**	**Fuel cost [€/MWh$_{fuel}$]**
Waste CHP*	20	4.5	0.18	0.98	4.2	-8.68
Gas CHP*	40	53	0.5	0.94	2.1	32.71
Gas boilers	100	-	0.96		5.4	32.71
Solar heating	6.1	-	1		1	0
Bio-oil	5.4	-	0.95		5.4	28.81
Geoth.+wood boiler**	12.5	-	1.35		5.4	28.81

**Income from electricity sales on el-spot day-ahead market was subtracted from the heat marginal price offer on the day-ahead heat market. These values were different for each hour depending on the marginal electricity price. Hence, they are not represented in this table but they can be downloaded from www.nordpoolspot.com website, for the year 2015, DK-West area.*

***Geothermal heat coupled with absorption heat pump driven by biomass for heat generation. Modeled as biomass boiler with η=135% as the geothermal heat was considered to be free.*

Gas is also taxed when used for energy production purposes at the rate of 27.7 €/MWh$_{fuel}$ [38]. Average electricity price development on the el-spot market until 2030 was adopted from [37].

Recap of all the technical and economic data used for feasibility calculation of WtE plant in both cases is presented in Table 2.

Table 2. Technical and economic data of Sønderborg WtE plant [36]

WtE plant Sønderborg		
Capacity	4.5	MW_e
	19.98	MW_{heat}
Total O&M	53	€/t
Investment cost	8,500,000	€/MW
Efficiency el	16.6%	
Efficiency total	90.5%	
Availability	92%	
Lifetime	20	years
Gate-fee	-27	€/ton
Incineration tax	44	€/ton
Feed-in premium	10	€/MWh_e
Real discount rate	4%	
Inflation	2%	

As per [20] and [25], waste import after the year 2025 will not be economically viable anymore; hence, in this analysis the imported share of waste had to be replaced by biomass. The biomass price for the case of Denmark assumed was 28.58 €/t and was taken from [39].

3.2 Case of the City of Zagreb

Unlike Denmark, the Croatian WMS is not designed to meet the EU goals. Also, there is no actual WM plan for the City of Zagreb so technologies from WM plan to 2015 [40] were used for definitions of possible scenarios. The scenario Without MBT is based on the primary separation of waste and waste incinerator, while the scenario With MBT added MBT plant. For the WtE plant, as there is no existing incinerator, the same facility as in Sønderborg was assumed for the hypothetical cases. The major difference in WM status and the level of maturity of solutions in this field gives the Croatian case study a fundamentally different outcome. In comparison to the Danish case, WM procedures, legislation, and implementation are far from being optimally solved, and Croatia is faced with difficulties to resolve these issues and fulfil the commitment regarding the WM goals [41]. In the City of Zagreb, 300,000 tonnes of MSW is collected per year out of which 21% is separately collected, while the rest is collected as MW. Since there is no actual WM plan, waste quantities in future years were estimated using LCA-IWM prognostic model [28]. Actual and estimated data of separately collected waste fractions are shown in Figure 4.

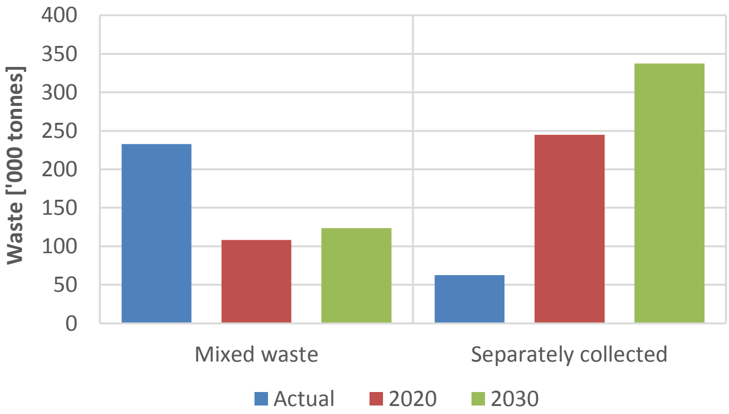

Figure 4. Waste collection quantities

Today, separately collected waste is mainly used for material recovery (production of compost and materials), while MW is disposed on landfill Prudinec. Because of this unsustainable practice, two scenarios which, when implemented, can reach EU goals were analysed. These scenarios were developed according to the previously described methodology.

Figure 4 shows possible waste collection data, if the primary separation of waste would be introduced and encouraged. The quantity of MW in the forecasted years has dropped by 50% in such scenario. This represents a challenge for planned WtE plant, but also a good opportunity to demonstrate the novel methodology of fuel switch between waste and biomass in the regions where a lot of work is yet to be done in WM.

There is no municipal waste WtE plant in Croatia, so there is no expected range of gate-fee value. Therefore this analysis will also help to determine the possible range of gate-fees in the case of the City of Zagreb. Waste incineration in Croatia is not taxed as in many other EU countries. WtE based CHP would be classified as high-efficiency CHP plant and the corresponding fixed feed-in tariff was used [42]. In new legislation WtE plants are recognized as a specific category and market-based tariff, with a proposed feed-in premium, but executive bylaws and regulations are not yet adopted. Furthermore, the heat price is constant as DH price in majority Croatia is considered to be a social aspect and regulated by politics through the government-owned operator. A discount rate of 5.5% is used which corresponds to discount rate in Public Private Partnerships in energy sector [43]. The analysis was performed on the same time-span as the electricity purchase agreement is signed for – 14 years.

4 RESULTS AND DISCUSSION

Based on previously described methods and case specific input data, results for the City of Zagreb and Sønderborg municipality are calculated.

4.1 Fuel data - case of Sønderborg municipality

In the case of the Danish municipality, expected waste increment trends are adopted – no major interventions in WMS are required and the most significant effect on waste generation are socio-economic movements. The impact of this trend on Sønderborg municipality incineration plant is shown in Figure 5.

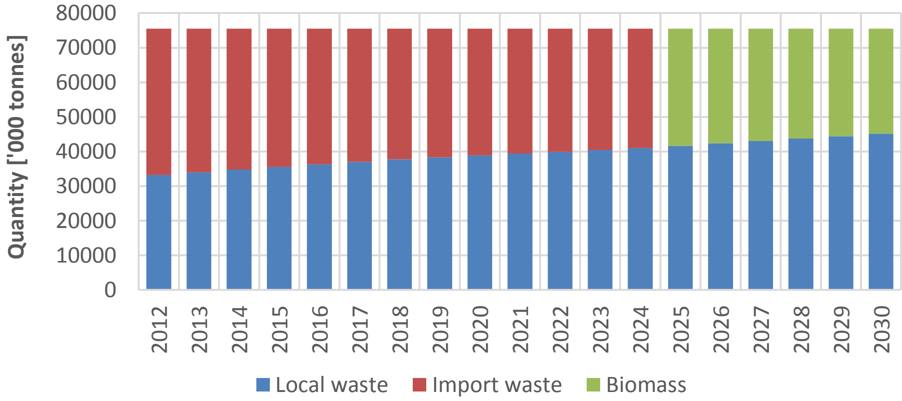

Figure 5. Sønderborg plants fuel ratio

Because of the anticipated economic growth, more waste is expected to be locally generated, reducing the need for waste import. It is expected that the import of waste will be profitable until 2020 and probably even until 2025, although with reduced profits [20]. Hence, for both scenarios carried out for the case of Sønderborg WtE plant, a replacement of imported part of waste with biomass was assumed from the year 2025 until 2030 to compensate for the waste decrease. It is important to note here that the biomass used as a fuel for energy purposes is not taxed in Denmark, as it is considered as a renewable energy source, while waste is taxed in order to promote recycling over the waste incineration and landfilling [35].

4.2 Fuel data - case of the City of Zagreb

The Sønderborg municipality data can be compared with projections for Croatian capital, Zagreb, where WMS needs major interventions. To satisfy EU legislation, projections with rapid implementation of separate collections are performed (Figure 6).

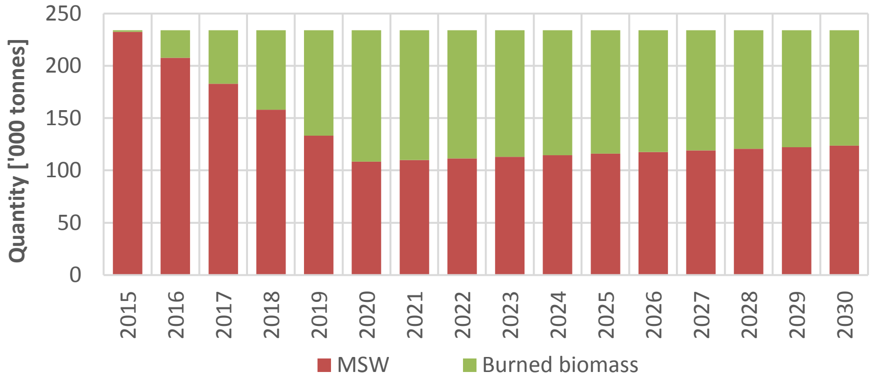

Figure 6. MW quantities - Zagreb

Until the 2020 quantity of MW is continuously reduced due to an increase of the share of separately collected waste. Rapid implementation of primary separation of waste to fulfil legislation goals for the year of 2020 reduces the quantity of waste that is collected in MW bins and overrides the increase in overall production of MSW due to trends described by WKC hypothesis. After 2020, a slower pace in the development of separate collection system is needed to satisfy legislation goals for 2030, so WKC hypothesis trends in waste generation override decrease in the quantity of MW due to an increasing in penetration and intensity of primary separation of waste. In the period up to 2030, reaching the economic threshold is not expected, so increscent of waste quantity due to WKC hypothesis trends is expected. In these circumstances, the WtE plant has to be planned to satisfy waste disposal needs but also needs to preserve the economic viability of the investment. In this case, the planned size of incineration plant was 233,000 tonnes. As waste quantity decreases, new fuel needs to be introduced – the biomass. Changes in WMS introduced lead to changes in waste composition. As the primary separation of waste decreases quantities of components with low LHV, overall LHV of waste increases. In the second part, after 2020 goals are satisfied, the forecast shows that drop in the relative share of plastics which is the main cause of decrease of LHV in later years.

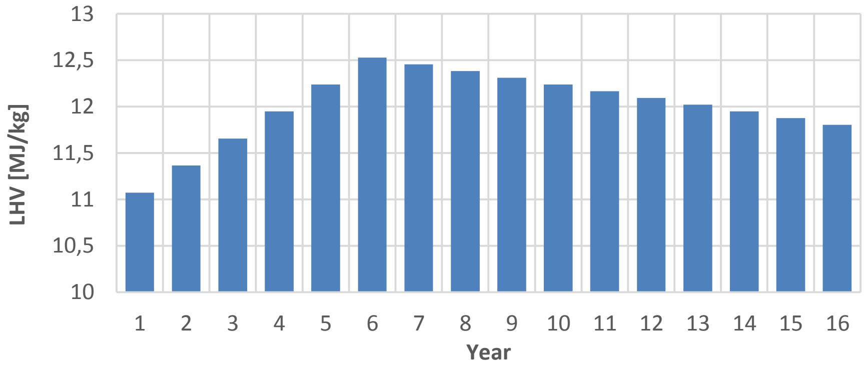

Figure 7. LHV forecast - without MBT

Further development of WMS can further decrease available waste for incineration. By the introduction of MBT, and by sorting of MW, more waste is extracted for material recovery which leads to increased demand for alternative fuels (Figure 8).

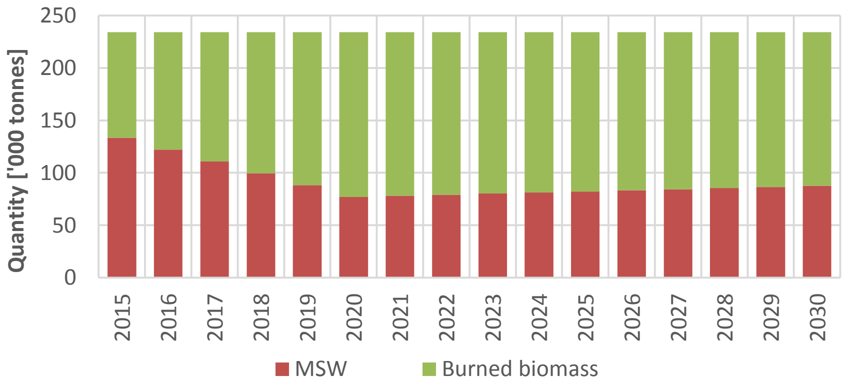

Figure 8. Fuel compensation - with MBT

The influence of implementation of MBT in the first year of the analysis on the same WtE plant operation was shown. While separation of waste components decreases waste quantity, it also has an influence on its heating value (Figure 9).

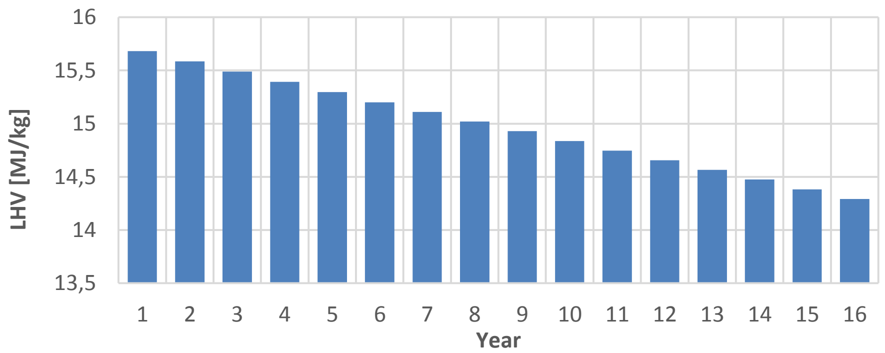

Figure 9. LHV forecast - with MBT

The initial increase in LVH of waste, in comparison with the case without MBT, is due to separation of metals and glass stream, which have no calorific value, and bio-waste stream, which has low calorific value, in MBT facility. The continual decrease of LHV of MW is mainly the result of the increase in primary separation of waste which reduces quantities of paper and plastics, which are not separated in MBT facility and go to RDF stream, in collected MW. Therefore, separated collection of other wastes from waste stream continually reduces LHV of MW on the entrance of the incinerator.

Shown LHVs are calculated only for the MW, while a mixture of waste with biomass would have higher values in the first case, and lower in the second case. This is logical because of constant LHV of biomass in continental Croatia, which amounts to 12.24 MJ/kg for wood biomass with 30% of moisture, which depends on a variety of wood species that are used.

While in the case of Sønderborg WMS is established and gate-fee prices are defined, in the case of Zagreb they are to be defined. For the initial value of gate-fees, mean European value of 110 € per tonne of waste was used for calculation of minimal needed values. The method for determining gate price of biomass at the location was elaborated in [44]. The biomass originates from the capacities of Forestry Offices in the neighbouring counties. The changes in the mean price of biomass on the plant's gate, which is in the range between 32.2 and 37.13

€/t in both cases, show that there is enough biomass for the case examined (Figure 10). These prices were calculated on the basis of the constant price of biomass on the forest road of 32 € per tonne and fluctuating transport costs that depend on the distance of the plant from forestry offices from which biomass have to be transported.

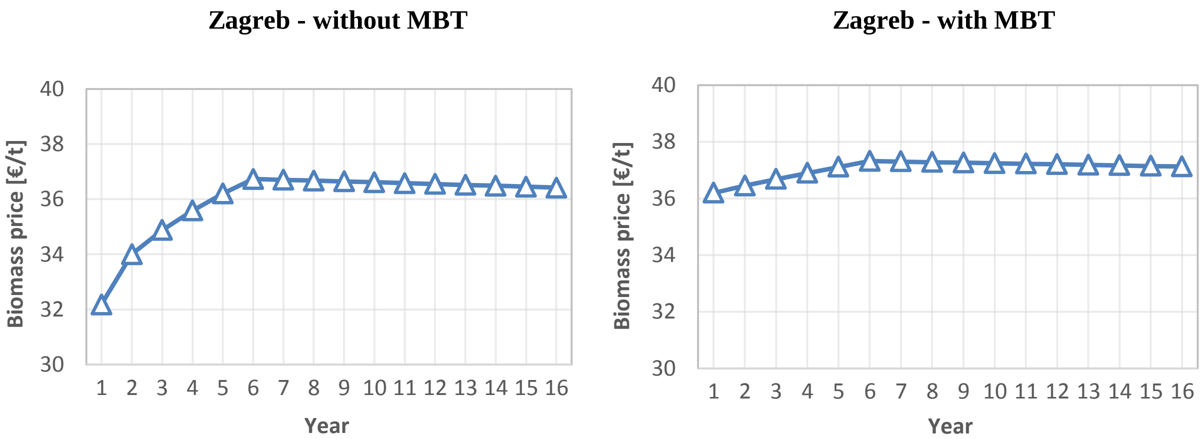

Figure 10. Biomass price

The price of biomass increases as needed quantity increases, and vice versa, price decreases as the need for biomass decreases, because the price is considered to be a function of distance only so that it changes with every new forestry office that is included in calculation when the range of biomass collection increases.

4.3 Economic analysis - Zagreb

All scenarios for the case of the City of Zagreb were calculated on the basis of the same incineration plant whose data for full load are shown in Table 3.

Table 3. Zagreb WtE plant data

WtE plant Zagreb		
Capacity	14.3	MW_e
	66	MW_{heat}
Total O&M[3]	51.6	€/t
Investment cost[3]	10,700,000	€/MW
Efficiency el	16.6%	
Efficiency total	90.5%	
Availability	92%	
Analysis period	14	years
Initial gate-fee	-110	€/ton
Electricity feed-in income[1]	73.6	€/MWh_e
Heat feed-in income[2]	34	€/MWh_t
Real discount rate[4]	5.5%	

[1] Taken from reference [42]
[2] Taken from reference [45]
[3] Taken from reference [5]
[4] Taken from reference [43]

Plant capacity was modelled on the basis of need for waste disposal without changing the existing WMS in 2015.

4.3.1 Scenario 1 – Without Mechanical Biological Treatment

Taking into account the influence of gate-fee on the price of waste collection, a yearly gate-fee was modelled as minimum gate-fee that ensures yearly cash flow of zero (after all expenses and investment cost). This also enables comparison of obtained data with Sønderborg case where WtE plant should not operate with a profit. On the same diagram data for the case without and with biomass, compensation can be observed. Also, minimal required constant gate-fee is shown in Figure 11 for the 14 years period. The average gate-fee, which denotes mean price through all 14 years period, in scenario Without MBT is 75.76 €/t, while volatile, which denotes yearly changing gate-fee value, span between 6.21 and 107.69 €/t When biomass compensation was introduced, average gate-fee drops to 20.22 €/t, and volatile is in the range from 6.05 to 26.74 €/t in absolute terms.

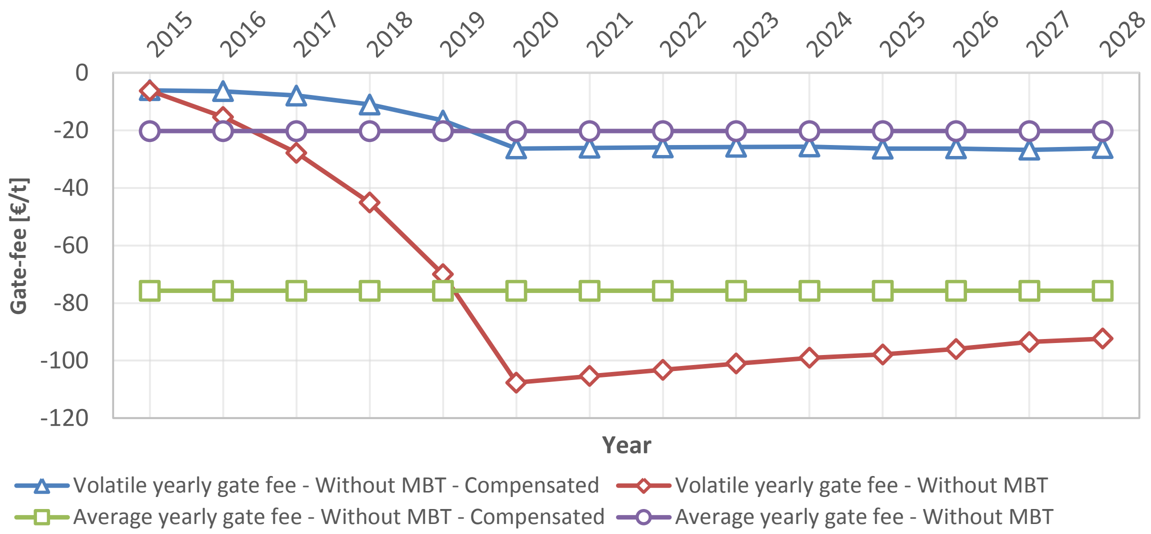

Figure 11. Volatile yearly and average gate-fees needed to recover investment and running costs (negative sign denotes that the fee is paid to the generation plant rather than by the plant)

It can be observed that volatile gate-fee increases rapidly in first years. This is due to decreasing MW amount to 2020. After the 2020 gate-fee volatility is reduced and it's almost constant in compensated case due to an increase in waste amount but a decrease in its heating value. In the not compensated case increase in waste, quantity has much greater influence than the decrease of its heating value so the yearly gate-fee decreases.

4.3.2 Scenario 2 – With Mechanical Biological Treatment

When MBT plant is introduced in WMS, the quantity of waste is reduced from the first year which increases the gate-fee. Values of gate-fees of this scenario are given in Figure 12. The average gate-fee in scenario With MBT is -159.11 €/t, while the volatile span between -48.33 and -206.94 €/t. When biomass compensation is introduced, the average gate-fee drops down to -14.22 €/t, and volatile is in the range from -25.52 to 19.73 €/t.

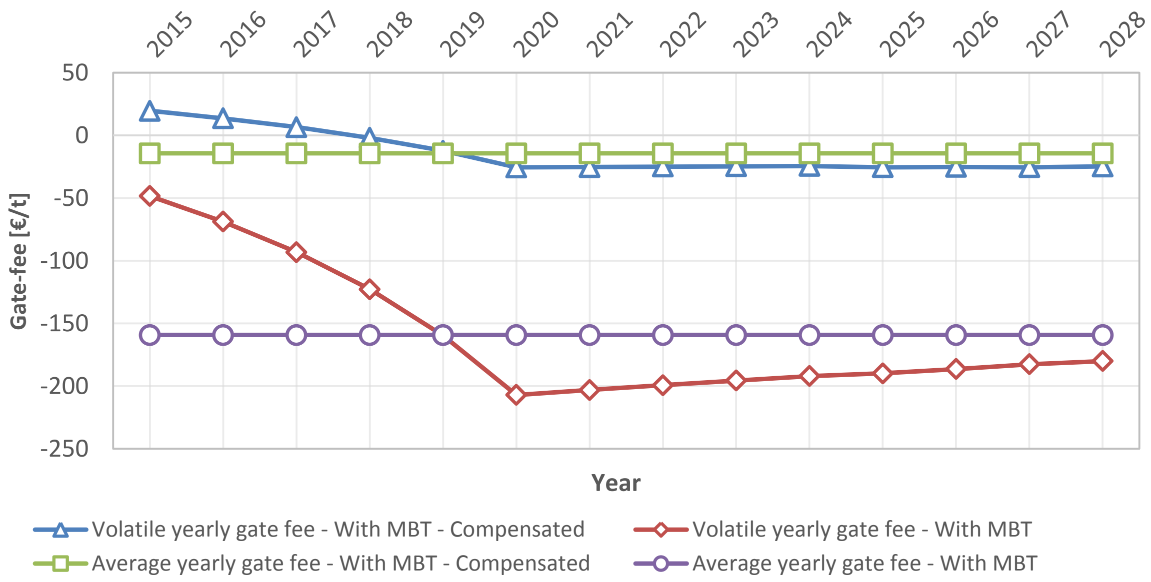

Figure 12. Volatile yearly and average gate-fees needed to recover investment and running costs (negative sign denotes that the fee is paid to the generation plant rather than by the plant)

From Figure 12, it can be noted that even though the gate-fee is vastly increased in comparison with the scenario Without MBT when biomass compensation is introduced the gate-fee needed for economic viability is smaller than in the first scenario. This is due to a big increase in combined heating value of fuel and through greater energy production.

4.4 Economic analysis - Sønderborg

All scenarios for the case of the Sønderborg municipality were calculated on the basis of the existing Sønderborg WtE plant whose data are shown in Table 2.

4.4.1 Scenario I – One energy market

Taking into account the expected future electricity market prices, as well as the rule that municipality owned WtE plants are not allowed to operate with profit, yearly gate-fees were obtained needed only to recover the investment and the running costs. On the same chart, an average fee until the year 2030 is presented. The average gate-fee could be used if the municipality would prefer a less volatile gate-fee price during the lifetime of the plant. These fees can be seen in Figure 13. The average gate-fee for this case was 14.8 €/t, while the volatile gate-fee was in the span between 9.2 and 28.34 €/t in absolute terms.

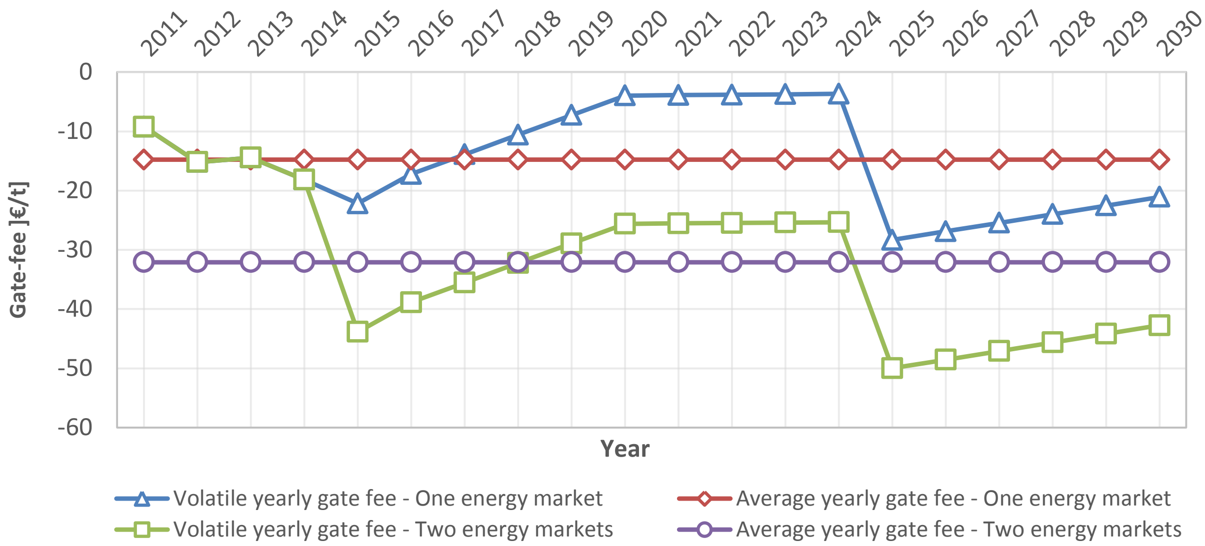

Figure 13. Volatile yearly and average gate-fees needed to recover investment and running costs (negative sign denotes that the fee is paid to the generation plant rather than by the plant)

Up to the year 2015, power prices on el-spot market were decreasing which meant that additional income from the heat market needed to be obtained, in order to recover the running and levelized investment costs of the WtE plant. From the year 2015 on, the average electricity prices are expected to increase, which will reduce the amount of income needed to be recovered from the heat market. The latter allowed the gate-fees to be reduced (in absolute terms).

It can be observed that the volatile gate-fee suddenly increases (in absolute terms) in the year 2025 as this is the year when importing waste will not be profitable anymore. Hence, in the year 2025, 41.1% of the fuel consisted of biomass and the rest from the waste collected within the municipality. As the biomass was more expensive than the waste, the gate-fee is needed to be raised in order to recover the biomass cost. The share of waste was then increasing up to the year 2030, in line with the forecasts of steadily increasing amounts of municipal waste, as discussed in the case study section. Using the gate-fees provided in Figure 13 and economic data provided in Table 2, a WtE would have an NPV equal to zero, according to the municipality rules. Thus, it would not operate with a profit nor it would subsidize the heat consumption.

4.4.2 Scenario II – Two energy markets

Nowadays, heat markets in Denmark are usually operated as monopolies owned by the municipalities. Although the latter can prevent excessive rises in prices due to the regulation, it can also discourage investments in energy efficiency as there is no real incentive for doing it. In order to assess the potential behaviour of the WtE plant on both power and heat markets, marginal prices based heat market was simulated in Matlab, while the power market simulation was carried out in EnergyPLAN. Both power and heat demand were modelled as fixed and known. Heat market was assumed to operate after the power market, i.e. by the time of the bidding on heat day-ahead market CHP producers already knew whether they were dispatched on the power market or not. It was assumed that the plant started to operate on the day ahead heat market in the year 2015.

Marginal heat prices obtained from the Matlab, as well as DH hourly demand, can be seen in Figure 14. It can be seen that during the time of high demand the heat prices were high, too. On the opposite, during spring and autumn, when there was a medium demand for the heat, the marginal heat price was volatile. Finally, during the summer season when the demand for heat was low, the heat price dropped accordingly.

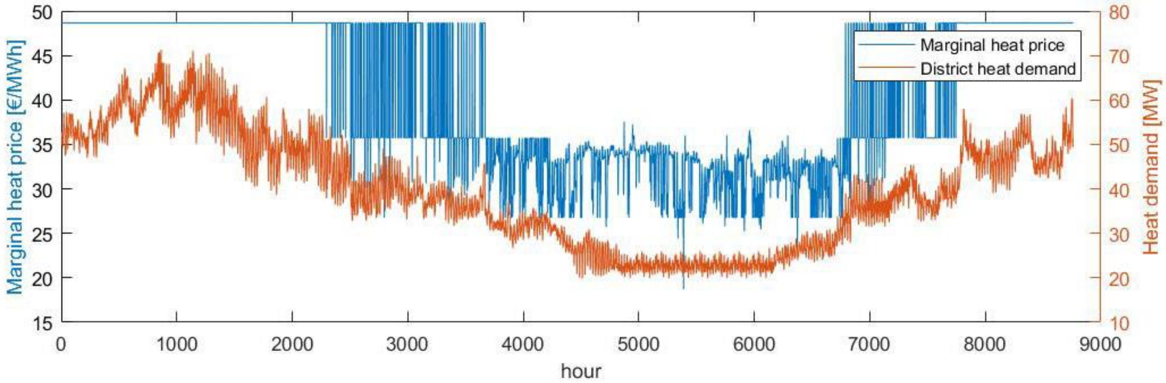

Figure 14. Hourly marginal heat prices (left Y axis) and district heat demand in the city (right Y axis)

Due to the marginal heat day-ahead market, the WtE plant was not dispatched during all the hours of the year on the heat day ahead market. As a consequence, the needed gate-fee to recover investments and running costs during the lifetime of the plant needed to be higher in absolute terms than in One energy market scenario. Dispatching of the WtE plant on the heat market is shown in Figure 15, while volatile and average gate-fees needed are shown in Figure 13, together with the results of the with One energy market scenario.

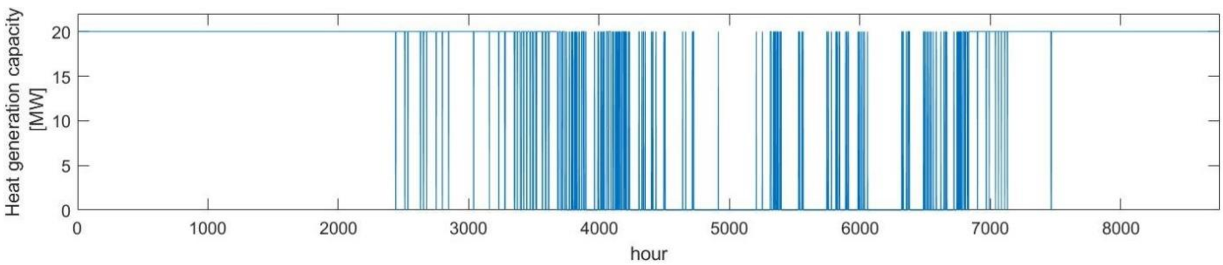

Figure 15. WtE plant operation on the heat day ahead market

By comparing Figures 14 and 15, one can spot that during the time of the high demand the plant was constantly operating on the heat market. However, when the demand started to drop, the WtE plant was not operating in a constant way due to the larger generation of plants with lower marginal cost (solar thermal DH plant) or due to the conditions on the power market. It is important to emphasize here that the second last term in Equation 2 shows that the WtE plant's marginal cost will be very dependent on the achieved power price on the el-spot market. If the obtained price is high, marginal heat price of the plant will be low and vice versa.

Finally, financial indicators of the regulated market and the marginal based day-ahead markets can be compared. As shown in Table 4, total yearly turnover on the markets is roughly the same in both cases. However, for the WtE plant, operating on both days ahead markets would be less beneficial, as it would receive 22.06% less income from the heat sales.

Table 4. Comparison of the regulated and marginal price-based day-ahead heat markets for the year 2015

	Regulated (averaged) prices	Marginal prices	Difference
Yearly turnover heat sales	14,770,440	14,889,000	0.80%
Waste CHP heat turnover	6,841,509	5,332,400	-22.06%

5 CONCLUSION

In this work, the analysis was carried out with the aim to analyse the influence of changes that are ahead of WtE plants. Therewithal, compensation for some of these changes is proposed. To test the approach, two WtE plants are taken as case studies, planned WtE plant in new EU member state which needs to fulfil EU legislation WM goals and in one old EU member state which is ahead of EU legislation in the area of WM. In the first case, the case of the City of Zagreb, the operation of planned WtE plant that satisfies needs of the city is analysed until 2030. In that period, because of needed WMS changes the majority of its capacity would be unused, less in the case of primary separation of waste alone and more in the case of introducing MBT plant. In these cases, fuel reduction is compensated with biomass which proved to be a sustainable way of alleviating this problem. This way the WtE plant is moved from the comfortable zone of regulated prices and put on the fuel market – the biomass market. The influence of this disturbance is tracked trough gate-fee volatility analysis which enabled monitoring of economic viability of municipality-owned plants because of their social-economic influence on the population through the price of the waste collection. This introduction of the WtE plant on fuel market did make this plant economically viable again by reducing needed gate-fee under the value of land-filling gate-fee of 53 €/t [46], without incineration tax and with high electricity subsidy. In the second case, the case of the City of Sønderborg, where all EU waste legislation goals are met, the operation of existing WtE plant on day-ahead electricity market and at the same time day-ahead electricity and heat market is analysed and compared. Because heat market does not exist at this time, it is simulated on the principle of the day-ahead electricity market. It is shown that introducing heat market to WtE plants operation increases minimum needed gate-fee on the yearly level and exceeds maximum levels that are expected in Denmark of 40 €/t. Due to the operation of WtE plant on the heat market, the waste collection price would need to be increased. However, this depends on the price of electricity, because dispatching time is dependent on marginal price which depends on electricity market price in every hour. Nevertheless, such open heat market could decrease heat price which could make it economically neutral on the basis of the municipality. Results of both of this analysis, carried out in completely opposite circumstances, show that WtE plant operation is economically viable during both of these transitions. Also, even though Denmark passed WM transition years ago and adapted to domestically waste reduction through waste import, its WtE plants will nevertheless need to undergo the same fuel switch which is designed for the transition of plants in the new EU member states.

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